PROSPECT – A Precision Oscillation and Spectrum Experiment

1. Name of Experiment/Project/Collaboration:
   PROSPECT – A Precision Oscillation and Spectrum Experiment
2. Physics Goals
   a. Primary:
      I. Precision measurement of the ^{235}U reactor antineutrino spectrum.
      II. Search for short-baseline oscillations as a probe of sterile neutrinos, and definitive test of the “reactor neutrino anomaly”.
   b. Additional:
      i. Development of scintillator-based radiation detectors in a high background environment.
      ii. Development of surface-based antineutrino detectors for reactor monitoring.
3. Expected location of the experiment/project:
   High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL)
4. Neutrino source: Reactor antineutrinos, 85 MW research reactor with HEU fuel.
5. Primary detector technology: Liquid scintillator, ^{6}Li doped
6. Short description of the detector

PROSPECT is a phased approach to the precision measurement of the reactor antineutrino spectrum and the search for short-baseline oscillation as a sign of new physics. The experiment consists of a 1 m^3 scale near detector at a distance of about 7 m from a reactor core (Phase I) and a 10 m^3 scale far detector at a distance of about 15 m at the High Flux Isotope Reactor at Oak Ridge National Laboratory (Phase II). See Figure1. The near detector will consist of a segmented ^{6}Li-doped liquid-scintillator target for detection of inverse beta decay (IBD) events. The doped liquid scintillator enables efficient event identification and powerful background rejection through pulse shape discrimination and coincidence requirements. The segmented detector design uses thin-walled optical separators with minimal mass to provide excellent light collection and energy resolution, uniform response, precise and unambiguous position information, and allows a flexible definition of the fiducial volume for systematic studies. The near detector design and HFIR deployment location allow for the movement of the detector over a distance of about 1.5m. This corresponds to translating the detector by more than a half a detector length covering an effective baseline range from ~7-11m. This capability enables good control and systematic checks of any spatially varying signal. The far detector (Phase II) will be a scintillator detector optimized to greatly expand the sensitivity of the oscillation search and study in detail any observed oscillation signal.

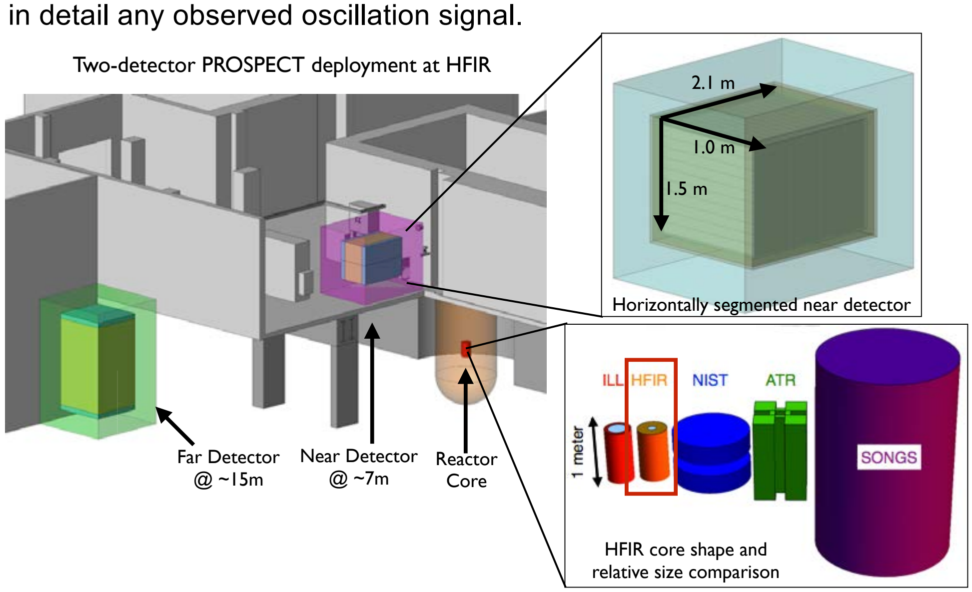

Figure 1: Left: A rendering of the two phases of PROSPECT at HFIR. Phase I comprises a movable near detector with an effective baseline of ~7-11m while Phase II includes an additional far detector at a distance

of ~15-20m baseline. Top right: The detector consists of optically segmented liquid scintillator volumes. The segmented array is oriented to minimize the baseline spread of observed neutrino events within each segment. Bottom right: HFIR has one of the most compact reactor cores which minimizes the uncertainty in the oscillation search from baseline variations.

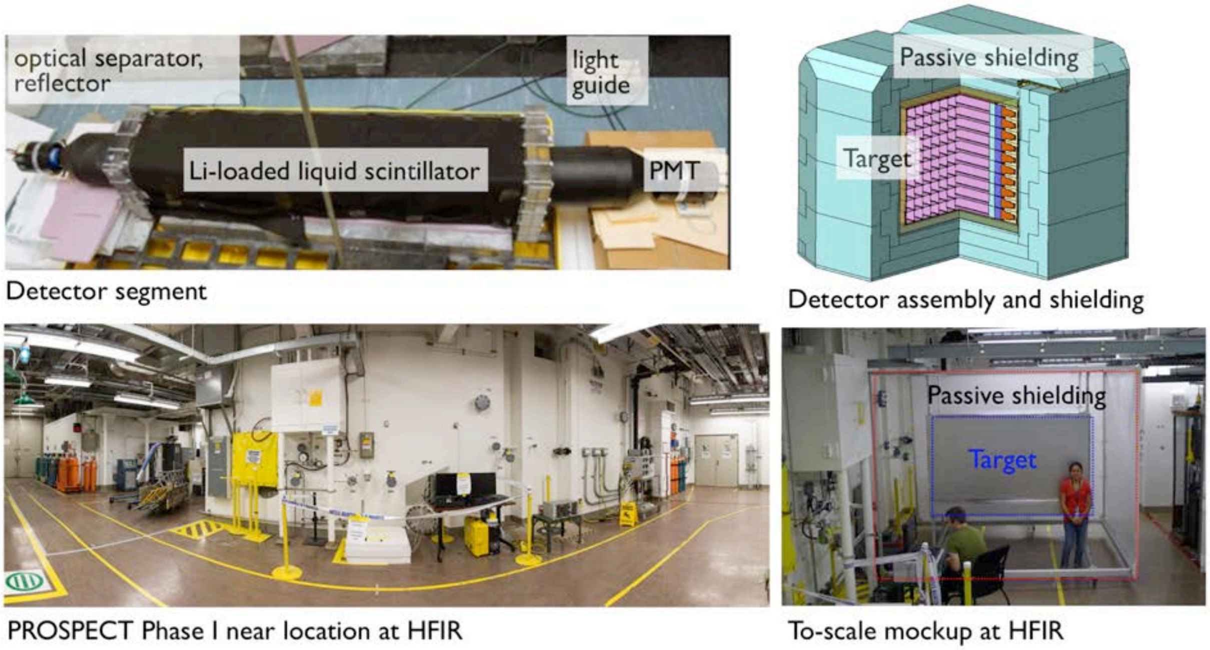

Figure 2: Bottom left: Phase 1 near detector location at HFIR. Bottom right: Mock-up of the placement of the near detector at its intended HFIR deployment location. Top left: Prototype 1m detector segment with Li-loaded scintillator and double-ended PMT readout. Top right: Conceptual model of detector assembly and shielding.

7. List key publications and/or archive entries describing the project/experiment.

Publications & Articles

I. *PROSPECT - A Precision Reactor Oscillation and Spectrum Experiment at Very Short Baselines*
J. Ashenfelter et al. (PROSPECT Collaboration whitepaper)
arXiv:1309.7647

II. *PROSPECT - A Precision Reactor Oscillation and Spectrum Experiment at Very Short Baselines*
T. Langford, for the PROSPECT Collaboration
arXiv:1501.00194

III. *Multiple Detectors for a Short-Baseline Neutrino Oscillation Search Near Reactors*
K.M. Heeger, B.R. Littlejohn, H.P. Mumm
arXiv:1307.2859

IV. *Experimental Parameters for a Reactor Antineutrino Experiment at Very Short Baselines*
K.M. Heeger, B.R. Littlejohn, H.P. Mumm, M.N. Tobin
Phys. Rev. D 87, 073008

V. *Search for Oscillations of Reactor Antineutrinos at Very Short Baselines*
S. Hans et al., Snowmass 2013 whitepaper
http://if-neutrino.fnal.gov/whitepapers/reactorUS_osc.pdf

VI. *U.S. Reactors for Antineutrino Experiments*
S. Hans et al., Snowmass 2013 whitepaper
http://if-neutrino.fnal.gov/whitepapers/reactorUS_reactors.pdf

VII. *Advanced Reactor Antineutrino Detector Development*
S. Hans et al., Snowmass 2013 whitepaper
http://www.snowmass2013.org/tiki-index.php?page=Received%20Whitepapers

Website: http://prospect.yale.edu

8. Collaboration

a. Institution list

US: BNL, Drexel, IIT, LBNL, Le Moyne, LLNL, NIST, ORNL, Temple, UW Madison, William & Mary, Yale

International: Waterloo, Canada; SYSU, China

b. Number of present collaborators: ~50 (US)

c. Number of collaborators needed: ~65 (US)

9. R&D

a. List the topics that will be investigated and that have been completed

i. ^{6}Li-doped scintillator with pulse shape discrimination capability (completed – Fig. 3-left)

ii. Background rejection in a segmented liquid scintillator detector with minimal dead material (ongoing – Fig. 3-middle)

iii. Development of low-mass, scintillator-compatible optical reflectors for detector segmentation (ongoing – Fig. 3-middle)

iv. Background studies and assessment in the vicinity of a research reactor (completed)

v. Site engineering and logistics studies at research reactor. Completed at 3 US reactors; HFIR selected for PROSPECT Phase I.

vi. Passive shielding of environmental backgrounds and detector operation with limited overburden. (ongoing - Fig. 3-right)

vii. Muon-correlated backgrounds in a segmented detector near surface (ongoing - Fig. 3-right)

viii. In-situ calibration of segmented scintillator detectors with short-lived isotopes (ongoing)

b. Which of these are crucial to the experiment?

Items i) through vii) are critical for the success of PROSPECT.

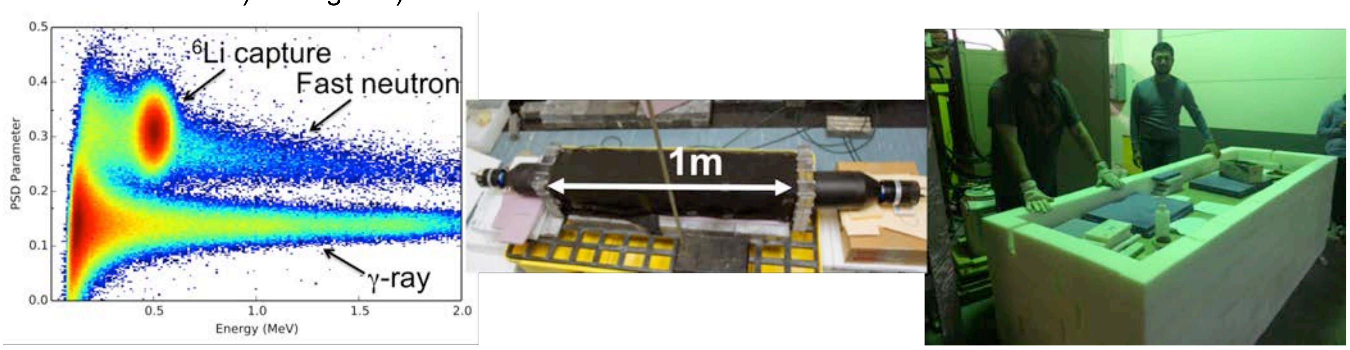

Figure 3: Left: Pulse shape discrimination of ^{6}Li neutron captures from fast neutron and γ-ray interactions. Middle: The PROSPECT20 full-scale segment prototype used for reflector testing, scintillator characterization and background studies. Right: Installation of PROSPECT20 at HFIR.

c. Timeline

Technically Limited Schedule

FY14-15	R&D including background studies and detector prototyping
FY15	Prototyping and test detectors
FY15-16	Construction and installation of a 2ton detector at near position (Phase I), R&D towards a second detector at far position (Phase II)
FY16-19	Operation of near detector (Phase I)
FY17-18	Planning for far detector (if desired based on results from near detector)

d. Benefit to future projects

i. Precision measurement of the ^{235}U reactor spectrum is input to models of reactor antineutrino emission and is useful for future reactor neutrino experiments such as JUNO and RENO-50.

ii. Measured reactor spectra will become part of the standard nuclear databases.
iii. Measurement of the reactor spectrum from a research reactor with highly-enriched uranium (HEU) core and in comparison to reactor operation is important for understanding the sensitivity of antineutrino detectors for reactor monitoring and safeguards.
iv. Development of doped, stable scintillator detectors with pulse shape discrimination is useful to the field of neutrino physics as well as radiation detectors in general.
v. Demonstration of antineutrino detection from a reactor with a detector on surface is relevant for applied antineutrino physics including reactor monitoring and safeguards.

10. Primary Physics Goal (Part I):

a. Expected results/sensitivity

Measurement of the ^{235}U reactor spectrum and comparison to models of neutrino emission from reactor. With the statistics of about 1M events in 3 years during Phase I PROSPECT will make the best measurement to date of the antineutrino spectrum from a HEU research reactor. The measurement of the spectrum will aid in understanding observed discrepancies in the reactor antineutrino spectrum and may explain the underlying cause for the observed “reactor neutrino anomaly”.

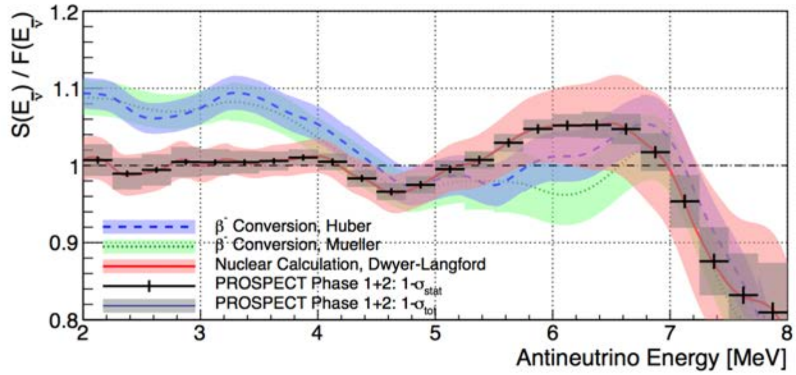

Figure 3: Three models of the energy spectrum of antineutrinos emitted by fission daughters of ^{235}U (see Phys.Rev.Lett.114 (2015) 012502 and references therein). The band includes a 1σ uncertainty from signal statistics and background subtraction as well as a 4.5%/$\sqrt{E}$ energy resolution. The systematic contribution of the backgrounds is assumed to be smaller. The gray band includes a systematic component from the energy model comparable to Daya Bay. We assume 1:1 signal to background.

b. List the sources of systematic uncertainties included in the above, their magnitudes and the basis for these estimates.

- Assumes absolute detector energy scale systematics comparable to Daya Bay.
- Assumes negligible uncertainty on the spectral shape of dominant backgrounds.
- Assumes negligible uncertainty due to temporal variations.

c. List other experiments that have similar physics goals.

NuLAT, STEREO, DANSS, Neutrino-4, and SOLID plan to detect antineutrinos from a reactor at short baselines and search for short-baseline oscillations. Some of these will measure the reactor spectrum with varying degrees of precision.

d. Synergies with other experiments

PROSPECT will provide the most precise measurement of the ^{235}U antineutrino spectrum of a research reactor, while Daya Bay, Double Chooz, and JUNO (proposed) provide precision information of the spectrum from LEU fueled commercial reactors with mixed fuel composition. Together they provide a comprehensive set of data of antineutrino spectra from nuclear reactors. This data set can be used to test flux and spectra predictions, provide important information for all future reactor-based measurements (basic or applied) and constrain nuclear models and predictions on which the reactor anomaly is partially based.

11. Primary Physics Goal (Part II):

b. Expected results/sensitivity

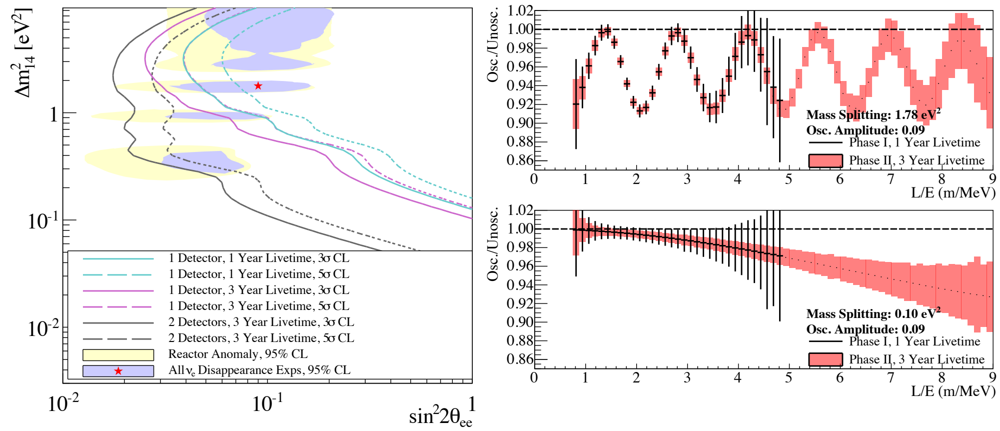

Figure 5: Left: Sensitivity to 3+1 oscillations with 1 detector (Phase I) and 2 detectors (Phase II) at 3σ and 5σ CL. Right: L/E distributions for Phase I and II illustrating the reach of PROSPECT's phased approach in studying an oscillation signal.

b. List the sources of systematic uncertainties included in the above, their magnitudes and the basis for these estimates.

- Assumes 100% uncertainty in absolute shape and rate: sensitivity purely from oscillations.
- Assumes 100% uncertainty in background rates.
- Assumes 1% uncertainty in cell-to-cell rate normalizations.
- Assumes 0.5% total uncorrelated bin-to-bin uncertainty to account for relative differences in energy scale and background shape uncorrelated between cells; improved handling in future.

c. List other experiments that have similar physics goals

NuLAT, STEREO, DANSS, Neutrino-4,and SOLID plan to detect reactor antineutrinos at short baselines, search for short-baseline oscillations, and measure the reactor spectrum with varying degrees of precision.

12. Experimental requirements

a. Provide requirements (neutrino source, intensity, running time, location, space,…) for each physics goal

The sensitivity plots shown above make the following assumptions about the reactor, detector, and measurement time:

Reactor

Neutrino Source:	Reactor antineutrinos from HEU reactor
Intensity:	85 MW thermal power, with a duty cycle of 42%
Running time:	3 years for initial running in phase I (near detector only)
	Or 3 years for running in phase II (near+far detector)
Location:	High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL)
	Location with 7-11 m baselines and ability to support detector exists and is available for PROSPECT at HFIR

Detector

Detector efficiency:	>30%
Position resolution:	15cm (by design, can be better)
Energy resolution:	4.5%/√E
Signal:Background:	1:1

Materials & Safety: Detector design and materials have been to shown to meet facility safety requirements (seismic, flammability, combustibility) at HFIR, ORNL.

13. Expected Experiment/Project time line

a. Design and development — 2013-2015

b. Construction and Installation — 2015-2016 (phase I, near detector only)
2018-2019 (phase II, near+far detectors)

c. First data — 2016

d. End of data taking — 2019 (phase I)
2022 (phase II)

e. Final results

   i. First measurement of the ^{235}U antineutrino spectrum from a HEU reactor (2017)
   ii. Test of the preferred region of the reactor anomaly at 3σ (2017)
   iii. Test of the preferred region of the reactor anomaly at 5σ (2019)
   iv. Precision measurement of the reactor antineutrino spectrum (2020)

14. Estimated cost range

a. US contribution to the experiment/project: US is lead and host country for this experiment. Universities and national laboratories in the US are involved in all aspects of the experiment. Their contributions range from design and R&D, to fabrication, testing and installation. The estimated cost range for a PROSPECT phase I near detector is $3-4M, including a 40% contingency.

b. International contribution to the experiment/project: Collaborators from China and Canada are contributing to the detector simulation, optimization of the experiment, and physics analysis. The PROSPECT collaboration is in discussion with potential foreign partners from China, India, and Europe.

c. Operations cost: Operations cost estimated to be $250k/yr. This includes support for consumables (gases, etc), spares for detector maintenance, as well as part-time support for professional operations and safety support as needed/required by HFIR.

15. The Future

a. Possible detector upgrades and their motivation

PROSPECT phase I consists of a single detector with about 2tons of active detector mass to make a first measurement of the reactor spectrum and search for short-baseline oscillation. A second detector at the far position would greatly enhance the sensitivity of the experiment to short-baseline oscillations and allow the experiment to study in detail an oscillation signal. See above and Ref [I].

b. Potential avenues this project could open up

   i. The observation of short-baseline oscillation as a signature of sterile neutrinos or other new physics would be a paradigm shift in particle physics and require an extension to the Standard Model. It would change the course of particle physics.
   ii. The measurement of the reactor spectrum benefits the modeling and understanding of reactor physics and in particular the understanding of antineutrino emission from a nuclear reactor. The data taken with PROSPECT together with other spectral measurements from Daya Bay, Double Chooz and RENO will form the basis for a standardized antineutrino spectrum for use in future reactor neutrino experiments.
   iii. High performance liquid scintillator with fast and thermal neutron identification capabilities is of great interest for future experiments and for applied radiation detection.
   iv. Demonstration of precision neutrino physics with a surface based detector would open the field of non-underground, non-accelerator neutrino experiments with a suite of potential applications such as reactor monitoring.